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REPORT NO. 1906

EVALUATION OF SIMPLE MODELS FOR THE  
ATTENUATION OF SHOCK WAVES BY  
VENTED PLATES

Fritz H. Oertel, Jr.

August 1976

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## I. INTRODUCTION

Blast associated with an accidental explosion is a danger to personnel, structures, and equipment. One simple protective measure is to build a massive total-containment structure. However, in many cases some type of vented structure is called for, such as: structures with frangible or blow-out panels, or the types of vented structures described in reference 1.

In order to better understand the suppression of blast by vented structures, BRL is conducting suppression tests on scaled-down models of such structures<sup>1</sup>; and, in a 10.2cm diameter shock tube, tests are being conducted on panels of those structures--for which the vented area is not easy to determine--and on panels with holes drilled in them<sup>2</sup>--for which the vented area is well-known.

In this report, which is done in conjunction with the Applied Technology Program of the Suppressive Shielding Program, we compare the shock tube experiments done by the BRL<sup>2</sup> and others<sup>3-5,7</sup> for single-

- 
1. C. Kingery, R. Schumacher, and W. Ewing, "Internal Pressures from Explosions in Suppressive Structures," BRL IMR 403, Ballistic Research Laboratories, Aberdeen Proving Ground, MD., June 1975. (Not Available)
  2. Private communication from Mr. C. Kingery, Ballistic Research Laboratories, Aberdeen Proving Ground, MD., November 1975.
  3. L. Dresner and C. V. Chester, "Attenuation of Shocks in Tubes by Orifice Plates," ORNL - TM-1750, Oak Ridge National Laboratory, Oak Ridge, TN., 1967.
  4. B. Anet, "Experimentelle Untersuchung über den Einfluss einer Einschnürung auf die Stosswellenausbreitung in einem Kanal Konstanter Querschnitts," Bericht SHB Nr. 68-17-G3, Studienkommission des EJPD für Zivilschutz, Zürich, Switzerland, 1968.
  5. B. P. Bertrand, "Shock Wave Transmission through a Large Restriction in a Constant Area Duct," BRL MR 1848, Ballistic Research Laboratories, Aberdeen Proving Ground, MD., June 1967 (AD 656744).
  6. L. L. Monroe, "Investigation of the Transmission of a Shock Wave through an Orifice," GALCIT Hypersonic Research Project Memorandum No. 46, Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, CA, September 1958.
  7. J. M. Ross, C. M. Nixon, and W. M. McMurtry, "A Shock Tube Study of Attenuation of Air Flow through Chokes," Suffield Technical Note No. 152, Suffield Experimental Station, Ralston Alberta, Canada, May 1966.



and multiple-plate arrays with the results of simple computation models<sup>5-8</sup>.

## II. PHYSICS OF THE INTERACTION

The interaction of a shock wave with a vented plate having a single venting slit is sketched in Figure 1, following a discussion in reference 4. In Figure 1a, the portion of the on-coming shock wave incident upon the obstruction is reflected by it, while the rest of the wave is transmitted into the hole undiminished in strength. After some time, the expansion wave shown propagating out from the opening serves to pump fluid into the hole and to attenuate the reflected shock wave.

The influence of viscosity is seen as a build-up of vortices at the entrance, Figure 1a. At a later time, this vortex becomes detached and is swept into the restriction, forming a contraction (*vena contracta*), Figures 1b-1e. Viscous effects are further in evidence as vortices are formed, Figure 1c, when the transmitted shock wave emerges from the restriction, later becoming detached, Figure 1e, as the shock wave expands to occupy the full area of the test section. For this particular case [incident shock strength:  $\sim 18$  psi (0.124 MPa)], an expansion wave propagates upstream against the flow, Figure 1c, causing an acceleration of the gas in the restriction until sonic flow is reached locally. It is noteworthy that sonic flow also exists at the smallest cross-section of the *vena contracta*, but a standing shock, Figures 1d and 1e, reestablishes subsonic flow.

Although the geometry of the vent in Figure 1 is not the same as for our cases, the concept should be equivalent. Some of the details of Figure 1 are supported by shadow photographs of shock waves interacting with thin plates vented by a single hole<sup>7</sup>, by schlieren photographs of this interaction for various "slit" geometries<sup>6</sup>, and by shadow<sup>9,10</sup> and interferencel<sup>10</sup> photographs of a shock wave leaving a tube.

- 
8. F. H. Oertel, N. Gerber, and J. M. Bartos, "The Modified Expansion Tube: Theory and Experiment," BRL R 1741, Ballistic Research Laboratories, Aberdeen Proving Ground, MD., September 1974, AD A001551.
  9. E. M. Schmidt and D. D. Shear, "The Flow Field About an M-16 Rifle," BRL R 1692, Ballistic Research Laboratories, Aberdeen Proving Ground, MD., January 1974 (AD 916646L). Also "The Formation and Decay of Impulsive, Supersonic Jets," AIAA Paper No. 74-531, AIAA 7th Fluid and Plasma Dynamics Conference, Palo Alto, CA, June 1974.
  10. F. H. Oertel, Jr., "Laser Interferometry of Unsteady, Underexpanded Jets," BRL R 1694, Ballistic Research Laboratories, Aberdeen Proving Ground, MD., January 1974 (AD 773664). Also Proc. Int'l. Cong. Instr. in Aerospace Simulation Facilities, CA Institute of Technology, Pasadena, CA, September 1973.



In the case of a plate with several holes, the picture is conceptually the same for each hole. However, the interaction of the expansion waves at each hole with the reflected shock wave must be considered, as well as the interaction of the shock waves emanating from each hole. It is not known how long it takes for these shocks to form into a uniform front.

For more complex geometries, the flow is even more complex. As a consequence, care must be taken to ensure that gages are placed far enough from the structure for meaningful and consistent pressure measurements to be made. For example, even for the simple case in Figure 1, a gage placed several tube diameters from the plate would read the pressure jump across a quasi-one-dimensional shock wave (Figure 1e). A gage placed near the plate would not (see Figure 1d).

### III. MODEL FORMULATION AND DISCUSSION OF SIMPLE MODELS - SINGLE VENTED PLATE

From the previous description, it is clear that the transmission of a pressure wave through a vented plate is highly complex, even for the case of the single vent opening in Figure 1. To make such a problem tractable, simplifying assumptions must be made. We have chosen to make a first order-type approximation, assuming that heat transfer, and local effects due to a sharp-edged restriction, such as: three-dimensionality, transiency, vorticity, flow separation, and turbulence, are of second order. The models shown in Figure 2 have been considered in this report.

In each model, we assume that for the incident and transmitted flows, steady, one-dimensional conservation equations for an inviscid, nonconducting, ideal diatomic gas are valid. For the transmitted shock wave, the flow is again steady and nearly one-dimensional far from the plate. And in each model, the assumptions made regarding the local flow through the vented plate reduce the complex flow through a sharp-edge restriction to the well-known case of steady, isentropic, quasi-one-dimensional flow through a convergent-divergent nozzle<sup>11</sup> -- as depicted in Figure 2. The nozzle has an area ratio  $A/A^*$ , where  $A$  is the unrestricted cross-sectional area of the tube and  $A^*$  is the sum of the cross-sectional areas of the holes. We assume that mass flow through the nozzle in each model is maximized; i.e., sonic or choked flow occurs at the throat, state [\*].

Other aspects of the models are slightly different:

In Model 1, Figure 2a, which has been found to give good agreement with properties measured in the hypersonic flow downstream of

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11. G. Rudinger, Nonsteady Duct Flow: Wave-Diagram Analysis, Dover Publications, Inc., New York, N. Y., 1969, p. 94.

the nozzle plate in the BRL expansion tube<sup>12</sup>, the incident shock wave is assumed to be fully reflected from the plate so that  $u_6 = 0$ . An isentropic, unsteady expansion--similar to that for the instantaneous opening of a diaphragm--then accelerates the stagnated gas so that it enters the convergent nozzle with a velocity  $u_6'$ . During expansion in the nozzle from the state [\*], the gas becomes underexpanded, requiring recompression. In this model, recompression is accomplished via unsteady, *isentropic compression*, the complementary process to the *isentropic expansion* needed in computing the expansion tube cycle. Of course, this process is not physically realistic. But, neither is the steady, isentropic nozzle expansion, which is merely an expedient of the one-dimensional simplified model that attempts to predict the end result of the actual unsteady free expansion from the constriction.

Model 2 is a composite used in reference 7 of Laporte's<sup>13</sup> model for flow into a constriction and Rudinger's<sup>11</sup> model for a shock wave diffracted by an increase in cross-section. Here, the incident shock wave is assumed to be partially reflected so that the gas flows into the nozzle with a velocity  $u_5$ . Conditions in region [5] are such that sonic flow will prevail at the nozzle throat. Then, the gas is accelerated by an unsteady, constant-area, isentropic expansion, as might be the case for a long constriction. After expansion in the divergent nozzle, recompression is accomplished by an inward-facing shock wave,<sup>11</sup> a more physically realistic process than the isentropic compression in Model 1.

Model 3 assumes that the incident flow stagnates behind a fully-reflected shock wave, a situation that is closely approximated for large values of  $A/A^*$ . However, since  $u_6 = 0$ , the continuity equation cannot be satisfied for the nozzle flow in this model. Here again, an inward-facing shock wave recompresses the steadily-expanded gas.

Based on our experience, we put forth Model 4 (see the Appendix) which uses an inward-facing shock wave in place of the isentropic compression used in Model 1, but is otherwise identical to Model 1. This inward-facing shock may locate itself in the divergent portion of the nozzle<sup>5</sup>, or move downstream behind the transmitted shock<sup>6</sup>.

- 
12. J. H. Spurk, E. J. Gion, and W. B. Sturek, "Investigations of Flow Properties in an Expansion Tube," BRL R 1404, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, June 1968, (AD 673109). Also AIAA Paper No. 68-371, AIAA 3rd Aerodynamic Testing Conference, San Francisco, CA, April 1968.
  13. O. La Porte, "On the Interaction of a Shock with a Constriction," Report LA 1740, Los Alamos Scientific Laboratory, Los Alamos, NM, 1954.



#### IV. RESULTS FOR SINGLE VENTED PLATE

Results of the computations for a single vented plate are shown in Figures 3, 4, and 5.

In Figures 3 and 4, transmitted overpressure (T.O.) is plotted against incident overpressure (I.O.) for several area ratios. Figure 3 shows a graphical comparison between the computation models; Figure 4 gives more comprehensive computations for Model 4.

Each curve for models other than Model 4 is arbitrarily terminated at a point which we choose to call the "transition" point. As used here, this point, which will be different for each model, represents the set of conditions for which Model 4 predicts that the inward-facing shock will stand at the exit of the hypothetical nozzle; that is, where  $M = M_7$  (See Appendix, Figure A1). To the left of this point, the shock stands somewhere in the divergent nozzle; to the right, it moves down the tube, following the transmitted shock wave. This right-hand segment is very nearly linear and can be closely approximated by a straight line out to values of incident overpressure (or incident Mach number) for which real gas effects become significant and a revised model is sometimes needed<sup>6,12</sup>. This linearity is evident for each of the other models as well.

Notice that the curves for Model 4 (Figures 3 and 4) do not pass through the origin as they should. The reason for this is that we stipulated sonic flow at the nozzle throat, thereby creating an artificial flow into the nozzle even for an acoustic wave (incident Mach number of unity, incident overpressure of zero). This assumption of the models is seen to have a small effect on the calculations; it is especially small at the larger area ratios. [However, it causes T.O./I.O. to become infinite as I.O. goes to zero, Figures 7a and 7b].

An estimate of the transmitted overpressure for an  $A/A^*$  not shown on Figure 4 and a given incident overpressure, can be obtained by interpolating between the curves. But, interpolation is not strictly linear (see, for example, the curves for  $A/A^* = 15, 20$ , and  $25$ ). A more useful representation<sup>7</sup> of the computed data (Model 4) for engineering purposes is shown in Figure 5. The abscissa is the fraction of blockage by the plate: it is zero when there is no restriction (T.O. = I.O.); and, it is unity when the restriction is a solid wall (T.O. = 0). Since the spacing between curves becomes smaller as I.O. increases, fewer curves are required than for Figure 4; and, at the higher values of I.O., linear interpolation between curves leads to small errors. This relatively weak dependence of T.O./I.O. on incident overpressure at moderate-to-large values will be shown more clearly later.

Some discrimination of such an estimate is sacrificed at high  $A/A^*$  ( $1 - (A^*/A) \rightarrow 1$ ), but we are primarily interested in  $A/A^* < 20$  ( $1 - (A^*/A) < 0.95$ ). Larger values of the area ratio are of little

practical interest, for, as seen in the insert on Figure 5, much of the shock attenuation possible is achieved before reaching high values of  $A/A^*$ . For example, at  $A/A^* = 20$ , 70-80% of the possible attenuation has been achieved for the range of incident overpressure considered.

The insert on Figure 5 also suggests that shock strength should be taken into account when selecting an area ratio for a desired attenuation level. For example, to achieve 70% attenuation of a 300 psi (2.07 MPa) wave, we need  $A/A^* \sim 20$ ; whereas, for the same attenuation of a 60 psi (0.414 MPa) wave, we need only  $A/A^* \sim 12.5$ . However, this trend does not appear to be borne out by experiment<sup>2,7</sup>.

## A. Comparison of Models

### 1. Incident Flow

There are two conceptually different models for the incident flow -- Models 1 and 2 (Model 3 is actually a limiting case of Model 2). However, when we compared computed values for state [6'] of Model 1 with those of state [5] of Model 2, we found that they were the same within the accuracy of the plotted data (actually  $< 1\%$  difference). Consequently, the two incident flow models are numerically equivalent, as alluded to by the results of Spurk *et al*<sup>12</sup> for the expansion tube.

We prefer the incident flow model of Model 1. Using it, we can compute flow conditions through to state [\*] directly; whereas, an iterative solution is necessary to compute the strength of the partially reflected shock of Model 2. No substantial savings in machine time was realized by using the incident flow model of Model 1 for these calculations, because each complete calculation took only  $\sim 0.07$  seconds. However, substantial savings could be realized if similar calculations were done taking chemistry and real gas effects into account.

The effect of the two numerically-different incident flow models can be seen on Figure 3 by comparing Models 3 and 4, since Models 3 and 4 are identical except for their incident flow models. For each value of  $A/A^*$ , the assumption of full reflection leads to a higher transmitted overpressure. In fact, at  $A/A^* = 2$ , Model 3 predicts a transmitted overpressure which is larger than the incident overpressure. This results, because the full reflection model does not satisfy the continuity equation for flow into the nozzle. As a consequence of this violation, results are expected to be poor for small  $A/A^*$  where velocity of flow into the nozzles can be significant. Improvement is expected as  $A/A^*$  becomes larger and entry flow velocity becomes negligible. For example, the difference between Models 3 and 4 at 100 psi (0.689 MPa) is  $\sim 15\%$  for  $A/A^* = 4$ , but decreases to  $\sim 8.7\%$  for  $A/A^* = 8$ , and  $\sim 4.3\%$  for  $A/A^* = 15$ . At even higher values of  $A/A^*$  and higher incident overpressures, the differences between models can become negligibly small.

## 2. Long Constriction and Several Vent Holes

At  $A/A^* = 4$  the comparison of models on Figure 3 includes Model 2 which accounts for the effect of a long constriction. Comparing Models 2 and 4, between which the only difference is the 'long constriction effect', we see that the effect is small--a percent difference of about 4% at "transition" and about 2% at 140 psi (0.965 MPa) incident overpressure. These differences are too small to measure with confidence. Experiment<sup>7</sup> shows that even in the actual case, where viscous effects would be included, the effect due to constriction length is small.

One analytic limitation of the simple models is that they cannot differentiate between a plate with a single vent hole having a certain area ratio and a plate with several vent holes having the same (effective) area ratio. However, experiments<sup>2</sup> have shown the differences in transmitted overpressure to be small.

## 3. Recompression Models

After the gas undergoes steady, isentropic expansion in the hypothetical nozzle, it is assumed to be recompressed by an isentropic process (Model 1), or by an inward-facing shock (e.g., Model 4). Since the incident flow model for Models 1 and 4 is the same, we can see the effect of the two recompression models by comparing their results on Figure 3. At the low area ratios, such as  $A/A^* = 2$ , where the entropy increase during recompression would be small, there is little difference between the models. But, as  $A/A^*$  increases and the amount of entropy increase during recompression becomes greater, the disparity between the results also becomes greater. For example, at  $A/A^* = 2$ , the difference is only  $\sim 1.5\%$ ; at  $A/A^* = 15$ , it is  $\sim 52.8\%$ .

## B. Comparisons with Experiment

### 1. Remarks on Experiments

The experiments we used for comparison with our computations, see Table I, were done in shock tubes for peaked waves<sup>2,7</sup> and step waves<sup>4,5</sup> incident upon single vented plates. (Pressure decays in time behind a peaked wave; it is uniform behind a step wave.) All plates, except for some used by Kingery<sup>2</sup>, were vented by a single hole. Vent areas and incident overpressures of interest to different experimenters seldom overlapped, as shown in Table I.; and, data are scarce.



TABLE I - SOURCES OF EXPERIMENTS USED FOR SINGLE VENTED PLATE

SOURCE	MEASURED INCIDENT	TUBE DIA (cm)	TYPE INPUT WAVE	AREA RATIOS	LOCATION AND TYPE
	OVERPRESSURE (psig <sup>†</sup> )				OF MEASURING STATION (Tube Dia's from Plate)
Kingery <sup>2</sup>	42, 113, 189	10.16	Peaked	2, 4, 10, 12.8	7 (Pressure)
Ross <i>et al</i> <sup>7</sup>	15, 30, 60, 75 90	91.44	Peaked	1.37, 2, 4, 8	13.2 & 19.4 (Shock Velocity)
14 Anet <sup>4</sup>	12.5, 15.5, 17.5, 48.57 28.4, 36.5		Step	8.2, 47.7, 94.5, 192.7, 487.5	2.2 (& 4.2) (Pressure)
Bertrand <sup>5</sup>	27, 85, 110	10.16	Step	23.3, 50.5, 96	12 to ~ 60 (5 locations) (Pressure)

<sup>†</sup>Multiply psi times  $6.895 \times 10^3$  to get pressure in Pascals.

In the experiments, pressure, or shock velocity (from which pressure can be computed), is measured ahead of and behind the vented plate. For experiments to be consistent with the computations, effects due to causes other than plate attenuation must be eliminated; that is, the tube must be calibrated so that the overpressure measured at a location behind the plate can be compared with the overpressure that would be measured there in the absence of the plate ( $A/A^* = 1$ ). The latter is the equivalent incident overpressure. The data of Anet and Bertrand, which are not known to have been corrected thusly, will be used as published and as "corrected" assuming a 19% shock wave attenuation.

Because of the complex character of transmitted wave development, gage location may strongly influence the magnitude of the measured quantity. Measurements should be made far enough from the plate for transient effects to have become small. For example, for large area ratios and step waves of intermediate overpressure, Bertrand<sup>5</sup> found that the transmitted waves were peaked. Overshoot was quite large for their highest incident overpressures and area ratio, and persisted for  $\sim 60$  tube diameters, although it decayed to  $\sim 10\%$  of its average steady value within 30 tube diameters. At their lowest area ratio,  $A/A^* = 23.3$ , the overshoot was much smaller.

Another example of transient behavior was noted by Ross *et al*<sup>7</sup> for peaked incident waves which did not steepen to re-form as a transmitted plane shock front until they had traveled 5-10 tube diameters from the plate. Anet<sup>4</sup> also observed this non-steepening trend for weak step waves, but for  $A/A^* \sim 200$ .

For references 2, 5, and 7, even if transient effects have not abated, gage locations are such that each transient state should be comparable. This may not be true for the data of reference 4, since the gages are much closer to the plate. However, judging by the discussion above, differences may be small, especially at  $A/A^* = 8.2$  where pressure overshoot should be small.

## 2. Comparisons

Figures 6 and 7 compare computations for Models 1 and 4 with measurements for several area ratios. The curves for Model 1 are again terminated at the "transition" point for Model 4.

On Figures 6a-f, Model 4 agrees best with measured transmitted overpressures over the entire range of area ratios and incident overpressures. It tends to predict higher values than were measured as incident overpressure increases, except at the higher area ratios. Overprediction is greatest at  $A/A^* \sim 4$ . The tendency to simplistically attribute the magnitude of this overprediction to dissipative effects should be resisted, because artificiality of the model also has an effect.

Figure 7 shows an important scaling effect noted in reference 7



and verified here for large-to-moderate incident overpressures by numerical computations: that the ratio of transmitted-to-incident overpressure is a weak function of incident overpressure. Actually, it appears that the measured ratio of overpressures is highest at the low incident overpressures and decreases to a nearly constant value as incident overpressure increases.

Here, again, we see that Model 4 predicts the measured values better than Model 1 over the full range of area ratios. The difference between the models becomes large for  $A/A^* > 10$ ; at  $A/A^* = 10$ , it is 23% or more. The trend for measured values to fall below the prediction for incident overpressures greater than  $\sim 60$  psi (0.414 MPa) is reversed at the two highest area ratios.

Good agreement exists between the measurements of Kingery<sup>2</sup> and Ross *et al*<sup>7</sup> for peaked waves over a fairly wide range of incident overpressures. Also, no substantial difference is evident, for a rather narrow band of incident overpressures, between the data for peaked waves of Ross ( $A/A^* = 8$ ) and that by Anet for step waves ( $A/A^* = 8.2$ ). The validity of the latter comparison is, however, clouded by a noteable difference in measurement location and by an unsubstantiated correction used on Anet's incident overpressures.

## V. RESULTS FOR A SERIES ARRAY OF PLATES

### A. Experiment

An experiment was performed by Kingery<sup>2</sup> on a series array of 1/4 inch (6.35mm) thick vented plates placed 1/4 inch (6.35mm) apart. Five holes of 1/2 inch (12.7mm) diameter were drilled in the plates on a circle of 1 inch (25.4mm) radius with its center at the center of the 4 inch (10.16cm) diameter circular plate -- an area ratio for each plate of 12.8. In the experiment, peaked shock waves with nominal incident overpressure of 69 psi (0.476 MPa) [54 psi (0.372 MPa) equivalent incident overpressure] were incident upon first one plate, then upon arrays of two, three, and four plates in series. Incident pressure, pressure at the center of the last plate in the array, and transmitted pressure were measured for each array; results are in Table II. In addition, the build-up and decay of pressure between the plates was recorded by oscilloscope traces of the pressure gage output.

### B. Computations and Comparison with Experiment

First, we applied the simple theory used for single plates to several plates in series by taking the wave transmitted by the first plate to be the wave incident upon the second plate. This procedure, which presupposes that spacing between the plates is large enough for a steady state to be reached, was repeated step-wise for each subsequent plate in the series. In this way, the overpressure

TABLE II - COMPARISON OF COMPUTATIONS (MODEL 4) AND EXPERIMENT FOR A  
4- PLATE SERIES ARRAY OF VENTED PLATES†

	<u>PLATE 1</u>			<u>PLATE 2</u>		<u>PLATE 3</u>		<u>PLATE 4</u>	
	I.O.	P <sub>6'</sub>	T.O.	P <sub>6'</sub>	T.O.	P <sub>6'</sub>	T.O.	P <sub>6'</sub>	T.O.
	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)
METHOD 1	54	234	14.7	55.1	4.0	23.6	1.3	17.4	1.2
METHOD 2	54	234	15.5	57.9	8.9	36.7	6.3	29.5	5.1
17 EXPERIMENT (Raw Data)	69	310	16.4	188	13.0	120	9.6	96	7.3
EXPERIMENT (Corr. Data)	54	234	16.4	141.9	13.0	90.6	9.6	72.5	7.3

†Multiply psi times  $6.895 \times 10^3$  to get pressure in Pascals.

transmitted through each plate of the array was determined from a working graph of Model 4, such as Figure 4, for  $A/A^* = 12.8$ . Maximum pressure on each plate was estimated by computing  $p_6$  for the wave incident upon each plate (See Fig. 2a and Appendix A. Actually, we should use  $p_6'$ , but for this area ratio,  $M_6' \approx 0$ , so  $p_6' \approx p_6$ ). Results of this method are compared with experiment in Table II.

A second method, which should be more applicable to this experiment, is suggested by the hypothesis of Baker *et al*<sup>14</sup> that a series of vented plates, each with a vent area ratio  $\alpha_i$  ( $i = 1, 2, \dots, n$ )  $= (A^*/A)_i$ , behaves like a single plate with an effective area ratio given by

$$\frac{1}{\alpha_{\text{eff}}} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \dots + \frac{1}{\alpha_n}.$$

For this method, the appropriate effective area ratios for the single, two-, three-, and four-plate arrays are 12.8, 25.6, 38.4, and 51.2, respectively. Transmitted overpressure read for each array from Figure 5 are shown in Table II;  $p_6'$  was again computed as explained above, using the transmitted wave strength for subsequent plates.

Examination of Table II shows that agreement between experiment and computations is reasonably good for the single plate. For subsequent plates, agreement is poor for both methods--ample testimony that the computation model as used for the case of the single vented plate is inadequate for this series array of plates. [Computations would probably better agree with measurements for these closely-spaced plates if the assumption of choked flow were removed. It appears from the discussion in the next section that mass flow through the array is not a maximum, as the choked flow assumption stipulates. It seems reasonable that if the flow is not assumed to be choked, a lower transmitted overpressure would be computed.]

Method 1 results in much lower values than Method 2. But, Method 1 does not yield lower values than Method 2 for *all*  $A/A^*$ . For example, it can easily be shown that for Model 4, two plates, each with  $A/A^* = 2$ , transmit a higher pressure than a single plate with an effective  $A/A^* = 4$ . Cross-over occurs at  $A/A^* < \sim 4$ , since two plates, each with  $A/A^* = 4$ , transmit nearly the same pressure as a single plate with  $A/A^* = 8$ . This observation is, of course, also true for Model 1 for which cross-over occurs at a slightly smaller value of  $A/A^*$ .

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14. W. E. Baker, P. S. Westine, P. A. Cox, and E. D. Esparza, "Analysis and Preliminary Design of a Suppressive Structure for a Melt Loading Operation," SWRI Technical Report No. 1, Southwest Research Institute, San Antonio, TX, March 1974.



Transmitted overpressure computed by Method 2 for the second through the fourth plates ranges from 30-35% lower than the measurements, but the pressure on each plate ( $p_6'$ ) is about a factor of three lower than the measurements (raw data). Even if we use the *measured* values of transmitted overpressure -- for which (from Figure 5) the arrays attenuate like single plates with area ratios of about 11.4, 15.6, 23.3, and 33.3, respectively -- the pressures computed from Equation (4) are still too low by factors of 2.5-3 (corrected data). [We feel justified in using the equations without "viscous" correction for the 4-plate case, because loss terms did not appear to be a factor in the comparison of computations with experiment for one plate below  $\sim 60$  psi (0.414 MPa) (see Figure 6).]

### C. Other Observations

Examination of the magnitude and shape of oscilloscope traces<sup>2</sup> of incident and transmitted wave pressures, and of pressures between the three arrays of closely-spaced plates, shows that between the plates, expansion of the transmitted wave is incomplete (its magnitude lies between the computed values for  $p^*$  and  $p_6'$ ), and that it never regains its shock-like shape until it leaves the last plate.

In essence, fluid appears to "leak" through the arrays in a way shown on Figure 8, which is a representation from the oscilloscope traces of the pressure on each plate at a particular instant in time. The time  $t_0$  is the time at which the pressure on the first plate is a maximum;  $t_2$ ,  $t_3$ , and  $t_4$  are the approximate times (after  $t_0$ ) at which the pressures on plates 2, 3, and 4, respectively, reach a maximum.

At  $t_1$  we see that a pressure wave has been transmitted through the 4-plate array very quickly -- in about one-tenth the time required for the pressure on plate 4 to peak. During this transit time, the pressure on the first plate has decreased only  $\sim 7\%$  from its peak value. This observation suggests that computations such as ours, which are, strictly speaking, applicable only to step waves, should also be applicable to transmission of a peaked wave with the same maximum incident pressure. The agreement, for single plates, between the data measured for a peaked wave ( $A/A^* = 8$ ) and a step wave ( $A/A^* = 8.2$ ) on Figure 6c seems to bear out this point, although data are insufficient for firm conclusions to be made.

In principle, we should also be able to compute the decay history of the transmitted pressures between and behind the plates by approximating the incident wave as a series of step waves of decreasing amplitude, because the transmitted wave is directly coupled to the incident wave to experimental accuracy. This has been shown by

scaling down the magnitude of incident waves from reference 7 and incident reflected waves from reference 2 using the ratio of peak transmitted to peak incident wave pressures, and then comparing the *resulting* "transmitted" wave shapes with the *measured* transmitted wave shape. Of course, we recognize that such an approximation is an over-simplification of the actual time-dependent, three-dimensional flow situation, but it may be useful. The main drawbacks of this simplistic approach are that the models simply do not predict the *magnitude* of the pressures accurately enough, and that the time when maximum pressure is attained cannot be approximated accurately (for example, from the known distance and an average of the computed velocities).

## VI. CONCLUDING REMARKS

Several steady, one-dimensional models of the interaction of a shock wave with vented plates have been compared with each other and with experiment. These models have one basic tenet in common -- simplicity. One model, Model 4, was formulated to combine the preferred features of the models: 1) Its entry model gave the same entry conditions as the partial reflection model, without requiring an iterative solution -- a potential time-saver. Allowing for partial reflection was shown to have a noticeable influence on transmitted overpressure at low-to-moderate  $A/A^*$ ; and 2) Computations were greatly simplified by replacing the actual transient, three dimensional expansion of the flow from the vent hole(s) by a hypothetical steady expansion in a quasi-one-dimensional divergent nozzle. The credibility of Model 4 was enhanced by the fact that its expansion model assumed a transmitted shock-structure consistent with the steady-state situation observed when a free jet expands from a tubular restriction into a larger tube<sup>10</sup>. That is, the transmitted shock wave was followed (for some conditions, see Appendix) by an inward-facing (recompression) shock wave.

Again, it should be stressed that the location of the measurement point downstream of the vented plate can be very important when measurements are being compared with computations. For example, for the 4-plate series array, the pressure was measured on the back of plate 4 to be 15.4 psi (0.106 MPa). If that pressure were used in conjunction with Figure 5, the array would appear to attenuate like a single plate with an effective area ratio,  $A/A^* = 13.3$ . This value is only slightly larger than the area ratio for each individual plate and quite different from the effective value of  $\sim 37$  computed for the pressure measured farther downstream. In making our comparisons, we tried to use consistent data (see earlier discussion of Table I).

Specific conclusions based on this work are:

For a single vented plate:

- 1) The number of computations is greatly reduced by the



fact that, for a given  $A/A^*$ , transmitted overpressure versus incident overpressure can be represented by a straight line (for a certain region -- see earlier discussion of Figure 4), and by the fact that the ratio of transmitted-to-incident overpressure is nearly constant over a wide range of interest (Figures 7a and 7b). The latter fact also reduces the number of experiments needed. 2) Model 4 agrees adequately with shock tube measurements of transmitted overpressure for fairly low incident overpressures (See Figures 6a-6f). For incident overpressures above "transition" from the hypothetical nozzle, a correction term is needed. 3) The models are applicable to step waves, but can be applied to peaked waves if the shape of the incident wave is known. 4) More -- and more careful -- data are needed to resolve the differences between computed and measured ratios of transmitted-to-incident overpressures at low incident overpressures (See Figures 7a and 7b), although our current interest in this region is small.

For a series array of vented plates:

1) These simple models cannot be applied with profit to the transmission of a shock wave by closely-spaced plates, since transient effects are obviously important. Neither of the two methods we tried (See Table II) predicted the peak pressure between plates adequately. The method using equivalent area ratio predicted the transmitted pressure best, but its predictions were still below the measured values, in contrast to expectations. 2) The experiment presently available is not a valid test for the models. Plates should have wider separation so that steady-state conditions will be approached. However, for most practical vented structures, the elements of the structure will likely be closely-spaced. [Unfortunately, data available in reference 3 for more widely-spaced plates did not include pressure measurements between the plates.] 3) For closely-spaced plates, experiment or a three-dimensional transient ("filling") code is required. Some simplification of the codes may be possible by taking advantage of the coupling between incident and transmitted wave decay mentioned earlier. Computations by Proctor<sup>15</sup> using their hydro-code show the expected trends for filling between plates of a 4-plate array for peaked and step incident waves.

## VII. RECOMMENDATIONS

It is recommended that:

1) Figure 5 be used to estimate the transmitted overpressure for given incident overpressure and  $A/A^*$ . 2) An experiment be done for widely-spaced plates (same plates, same incident wave strength)

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15. Private communication from Mr. J. F. Proctor, Naval Surface Weapons Center, White Oak Laboratory, Dahlgren, VA, October 1975.

to see if our model is appropriate for that case. And, an experiment be done for the 4-plate array at a higher incident overpressure, where losses appear to be greater. 3) The feasibility of relaxing the choked flow assumption be examined; and, if it is feasible, calculations be done for a series array of plates and compared with experiment. 4) An experiment be done with step waves incident upon single and multiple-plate arrays to quantify the effect of a step wave as opposed to a peaked wave on pressure between the plates. 5) The feasibility of simplifying applicable hydro-codes by assuming direct coupling between the decay of the transmitted wave and the known decay of the incident wave be examined; a considerable saving of computation time may be realizable.

#### ACKNOWLEDGMENTS

The help of Dr. Kevin S. Fansler, who programmed Model 4 for the computer, is gratefully acknowledged. Discussions with Dr. C. W. Kitchens regarding flow through the series array of plates are also gratefully acknowledged.

#### ADDENDUM

Analysis of some of the data referred to in reference 2 was completed after completion of this report. An empirical relationship was found assuming that the ratio of transmitted-to-incident overpressure is a function of area ratio alone. That relationship<sup>16</sup>,  $T.O./I.O. = 1.164 (A/A^*)^{-0.5135}$ , is shown plotted on Figure 5 (insert). It is a least squares fit to data for single plates with vent area ratios from 2 to  $\sim 20$ .

It is also noteworthy that Kingery<sup>2</sup> found good agreement between transmitted overpressures (T.O.) measured behind two-, three-, and four-plate arrays and transmitted overpressures computed for corresponding incident overpressures (I.O.) using the above equation. The area ratio for each array was computed using the equation on page 18 of this report.

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16. C. Kingery and G. Coulter, "Shockwave Attenuation by Single Perforated Plates," BRL Memorandum Report (to be published), Ballistic Research Laboratories, Aberdeen Proving Ground, MD.



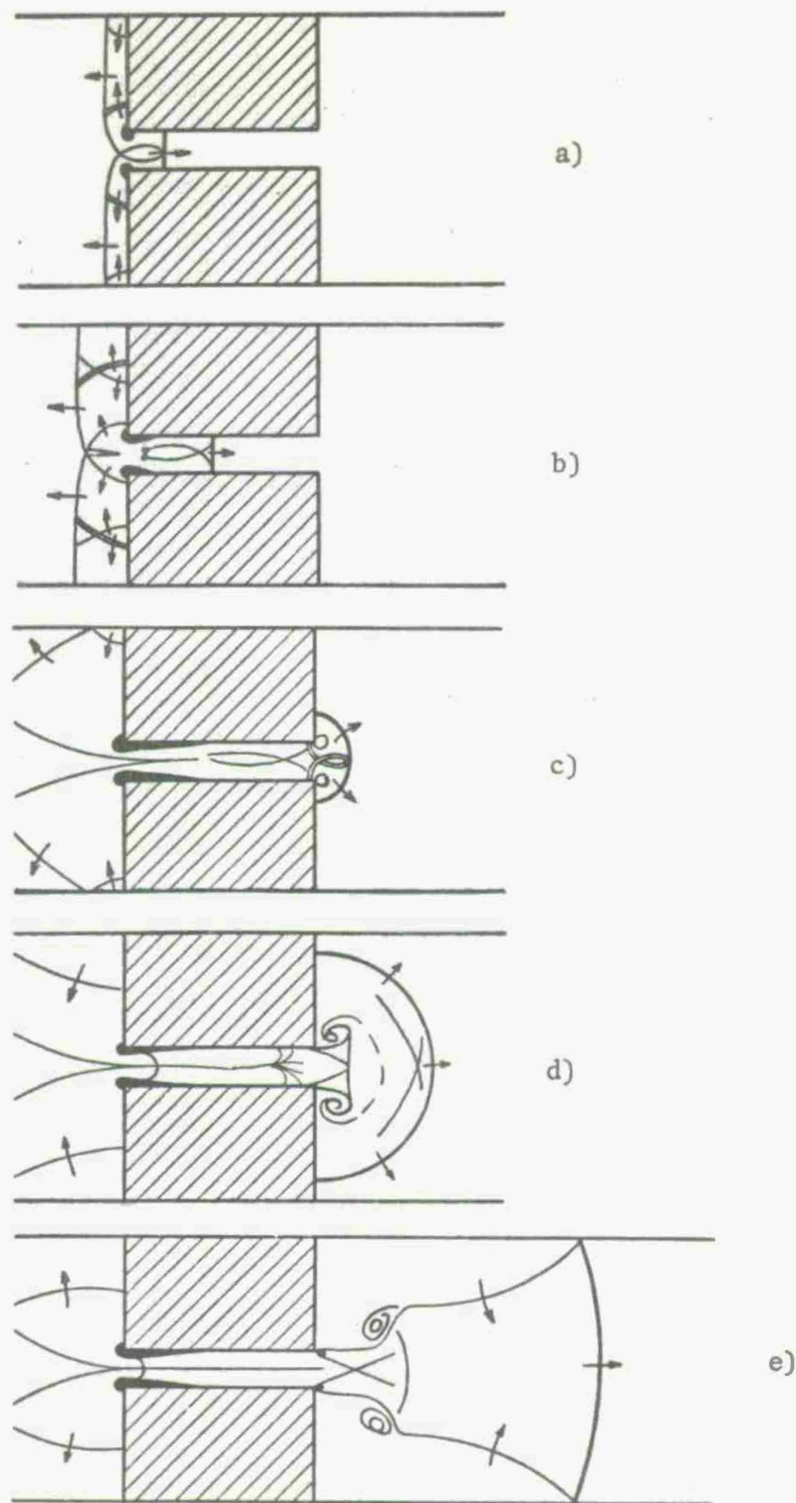
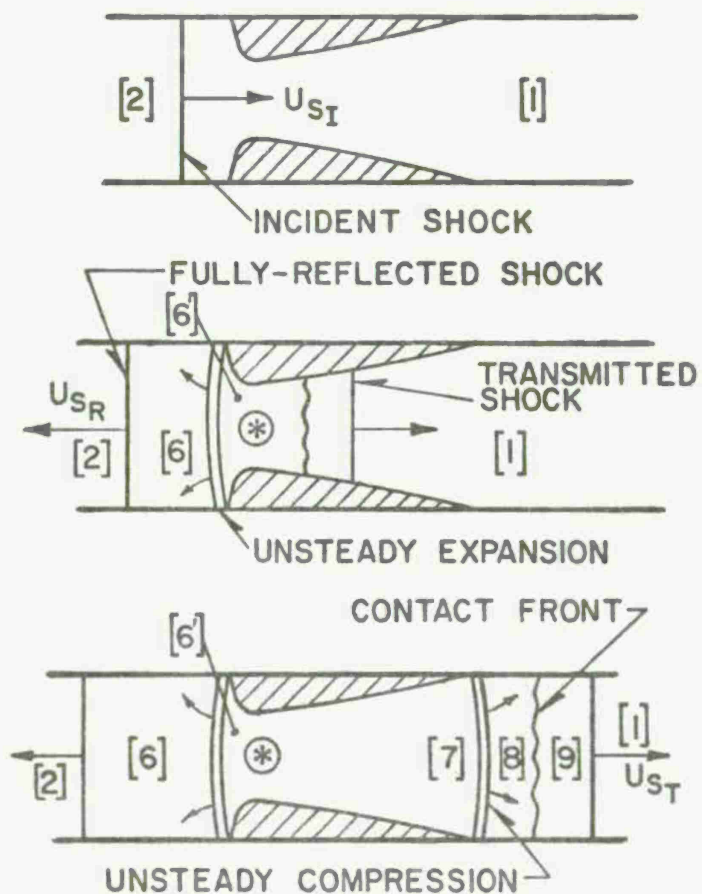
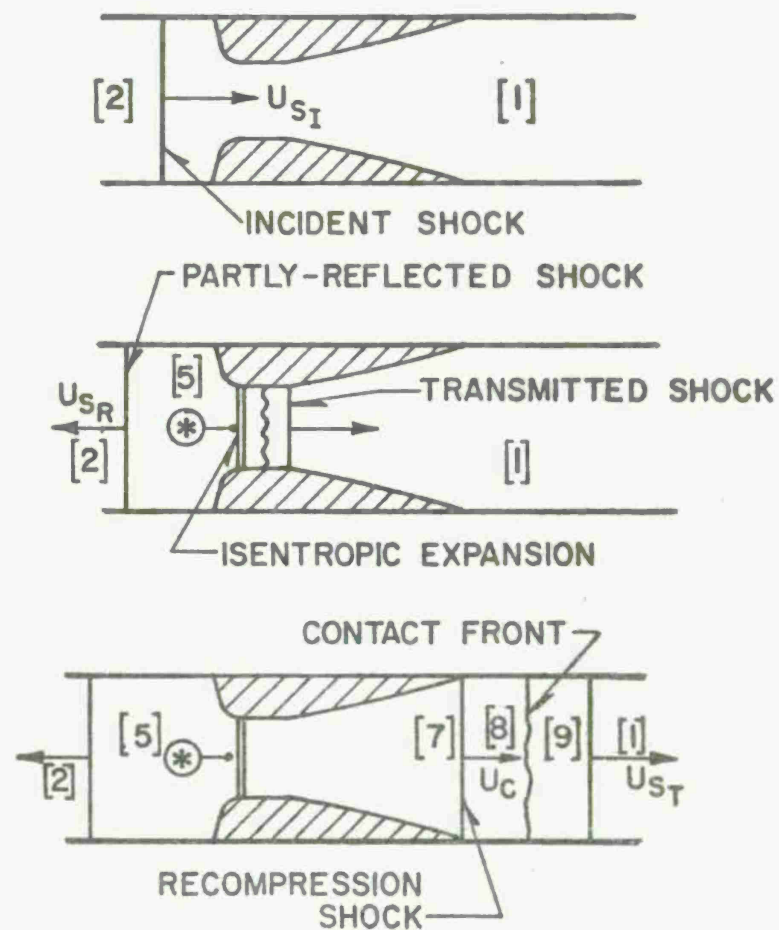


Figure 1. Stages During the Transmission of a Shock Wave Through a Single Slit in a Plate after Reference 4.

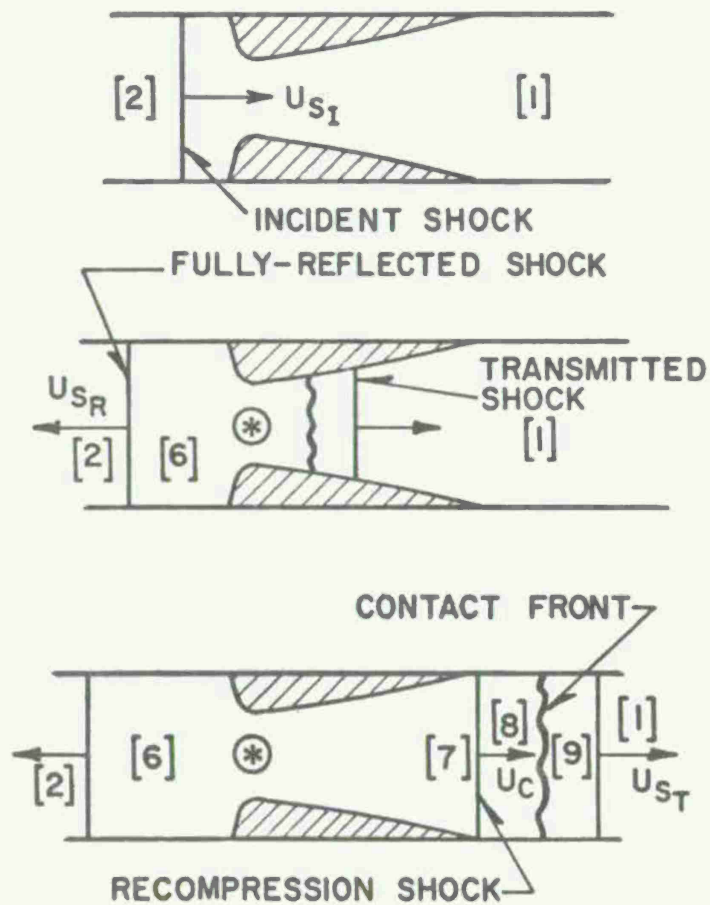


a) Model 1

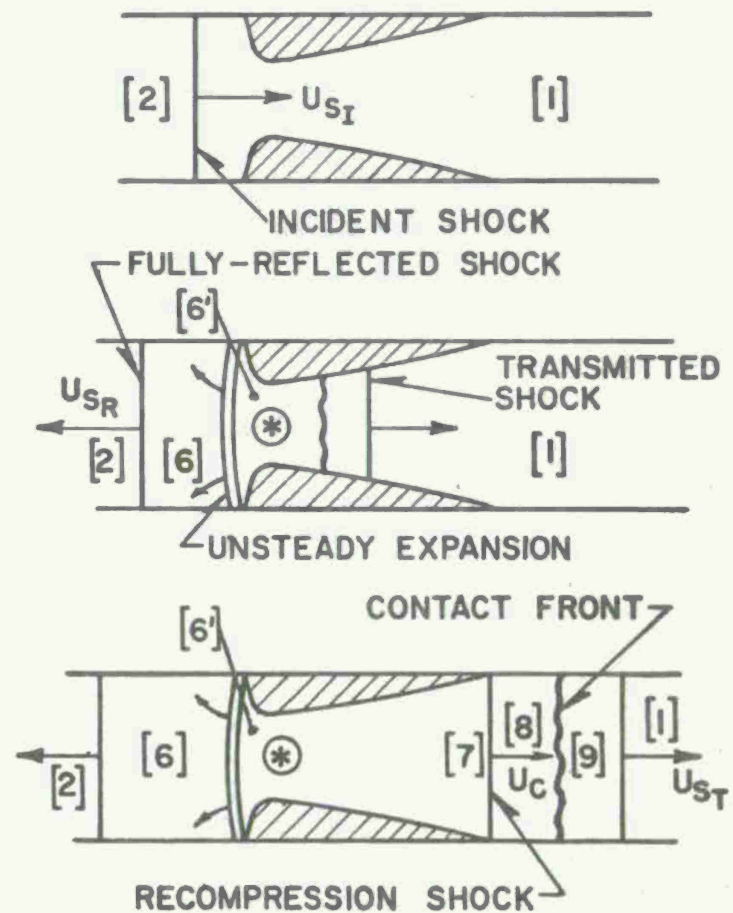


b) Model 2

Figure 2. Sketches of Flow Models. Flow processes are symbolic only.



c) Model 3



d) Model 4

Figure 2. Sketches of Flow Models. Flow processes are symbolic only.

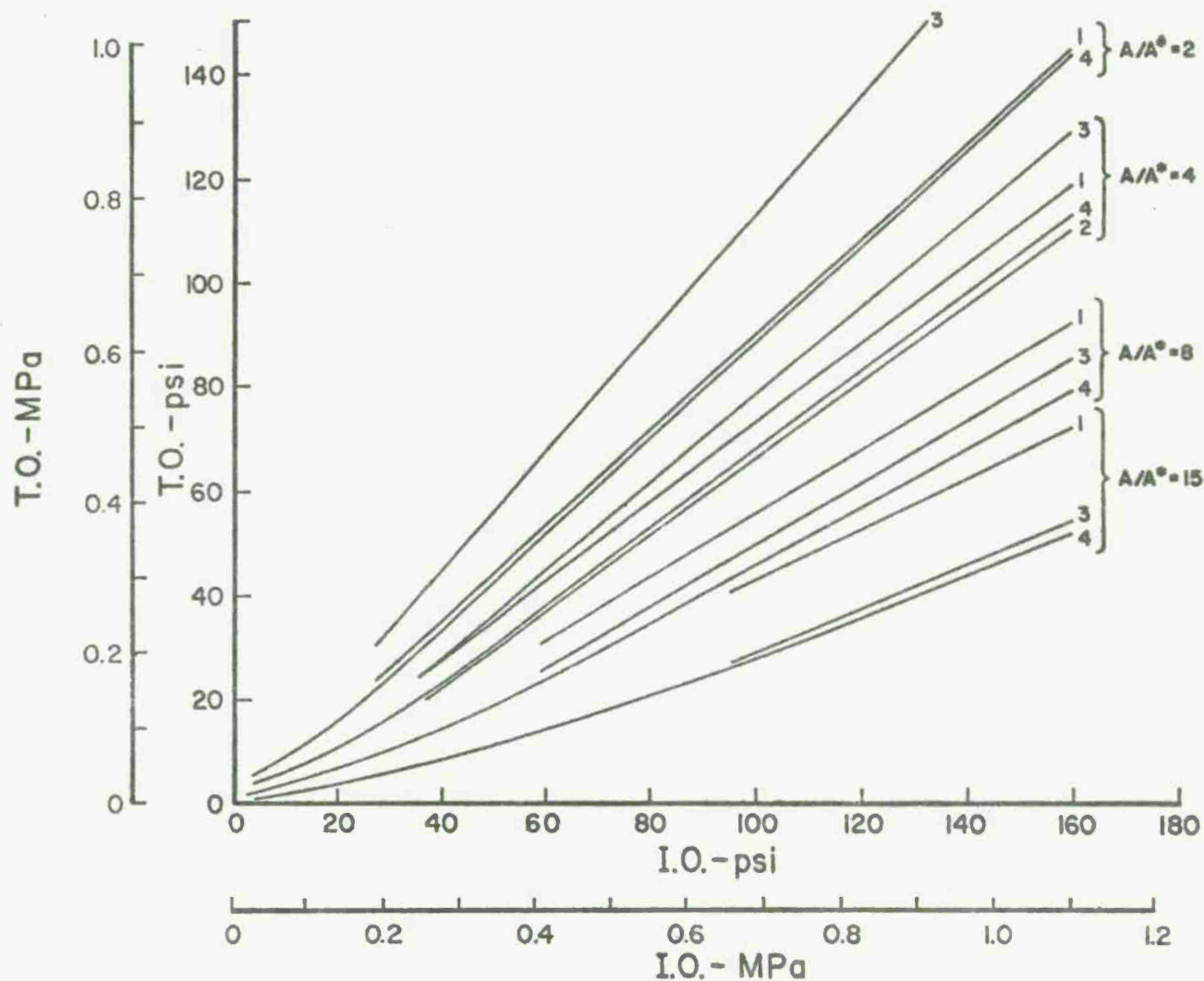


Figure 3. Comparison of Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for Flow Models,  $A/A^* = 2, 4, 8$ , and 15. 1, 2, 3, and 4 refer to models 1, 2, 3, and 4 respectively. Pressure is given in pounds per square inch (psi) and in millions of Pascals (MPa).

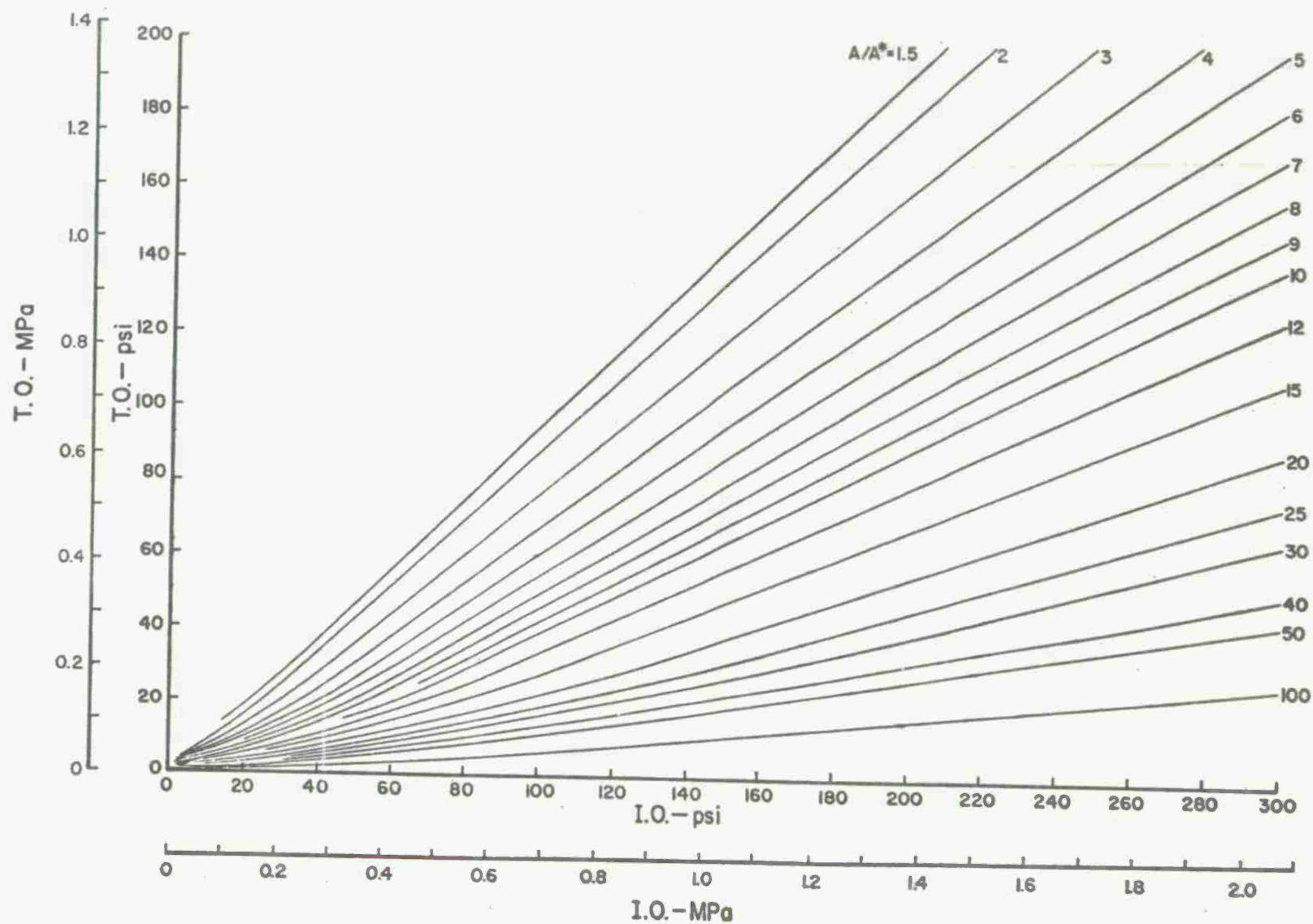


Figure 4. Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for Model 4;  
 $A/A^* = 1.5 - 100$ .



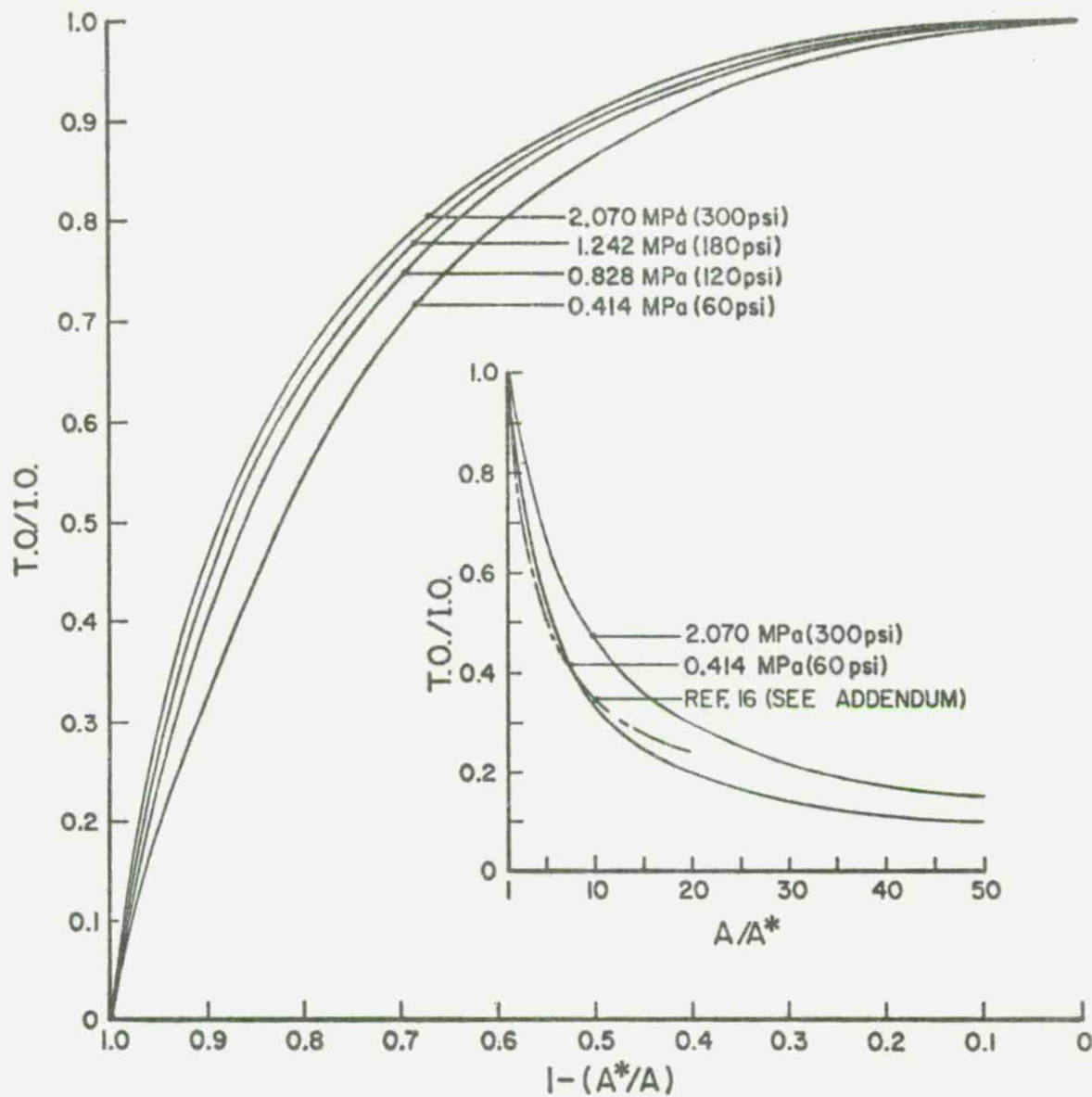


Figure 5. Ratio of Transmitted-to-Incident Overpressure ( $T.O./I.O.$ ) Versus Fraction of Blockage by the Plate for Model 4. Insert:  $T.O./I.O.$  Versus Area Ratio. The free parameter is incident overpressure in millions of Pascals.

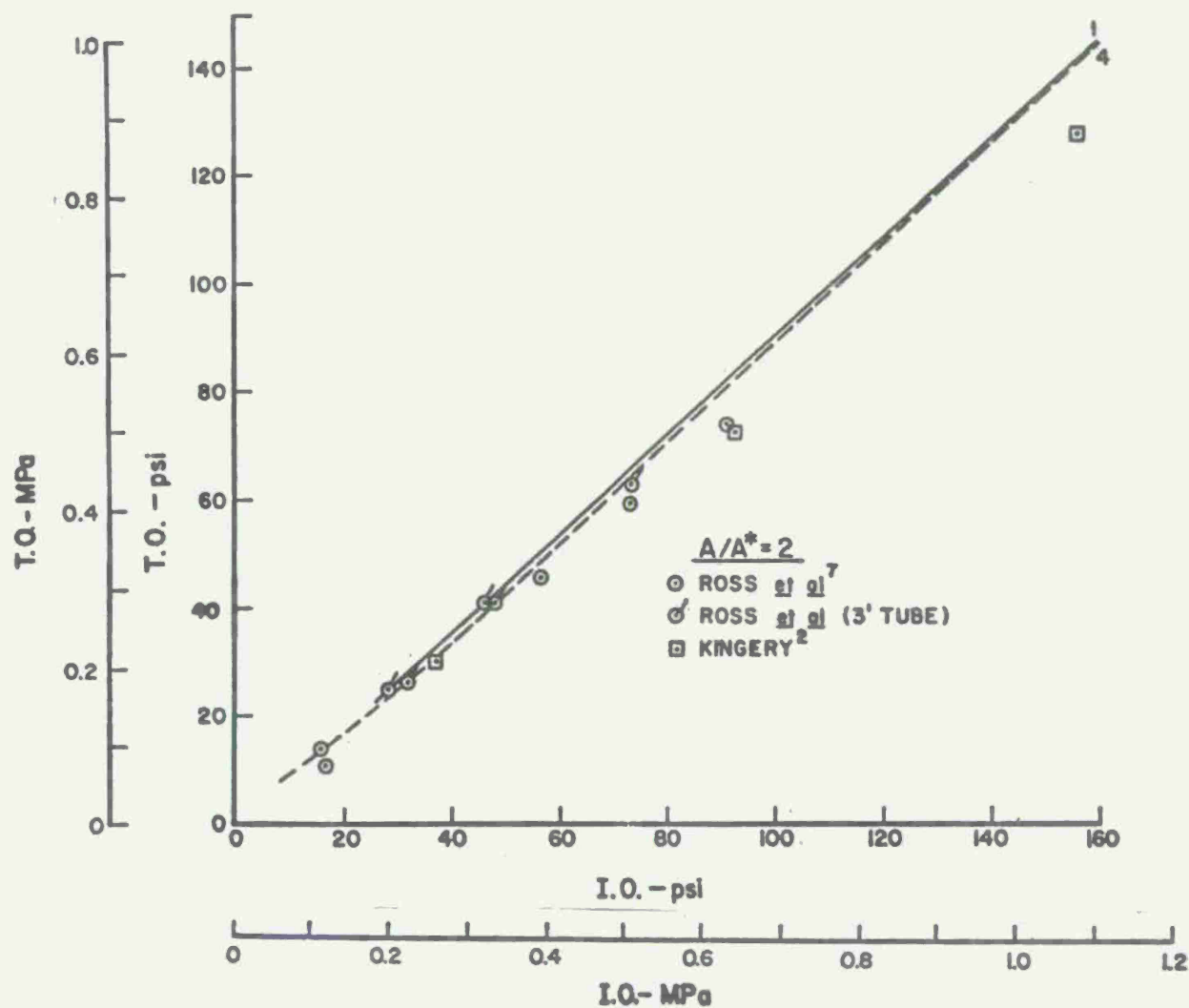


Figure 6a. Comparison of Experiment with Models 1 and 4: Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for  $A/A^* = 2$ .



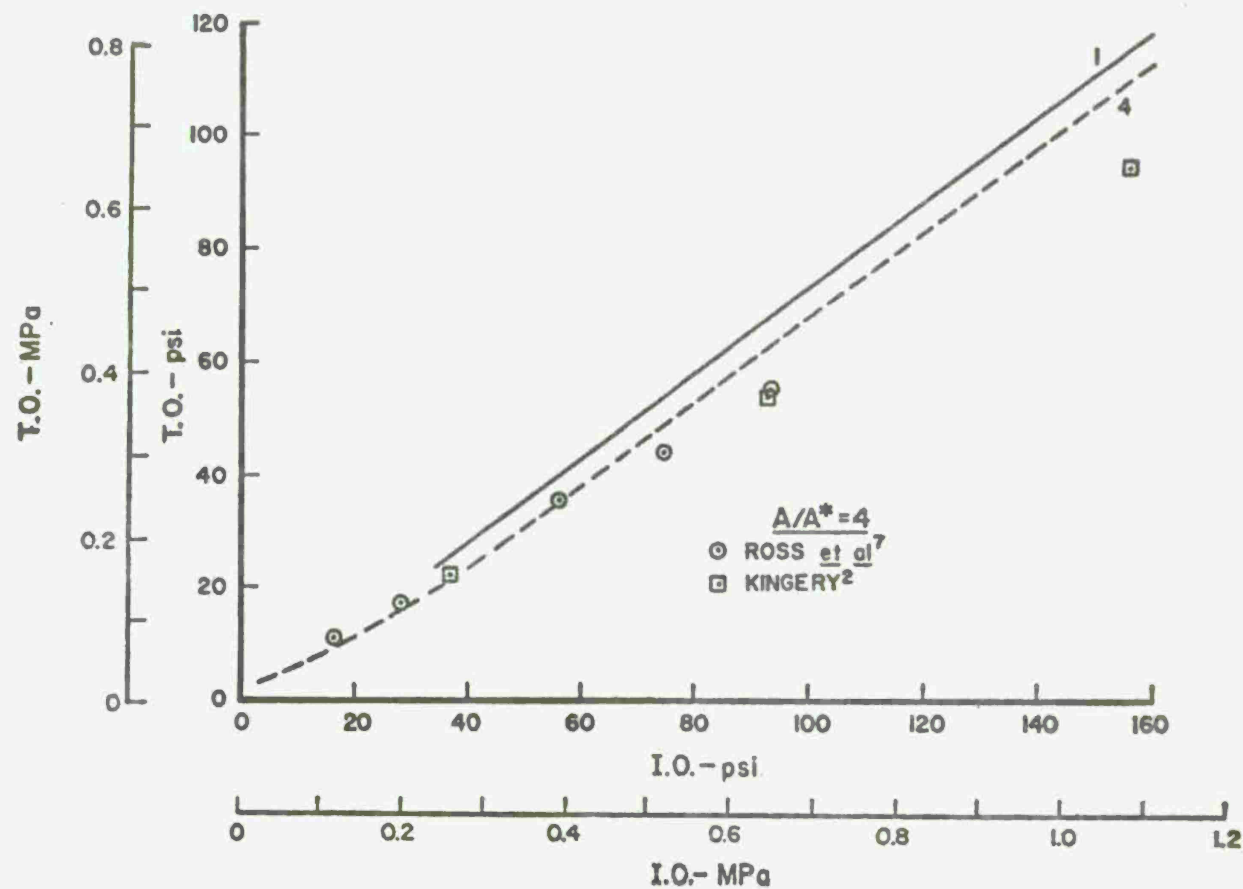


Figure 6b. Comparison of Experiment with Models 1 and 4: Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for  $A/A^* = 4$ .

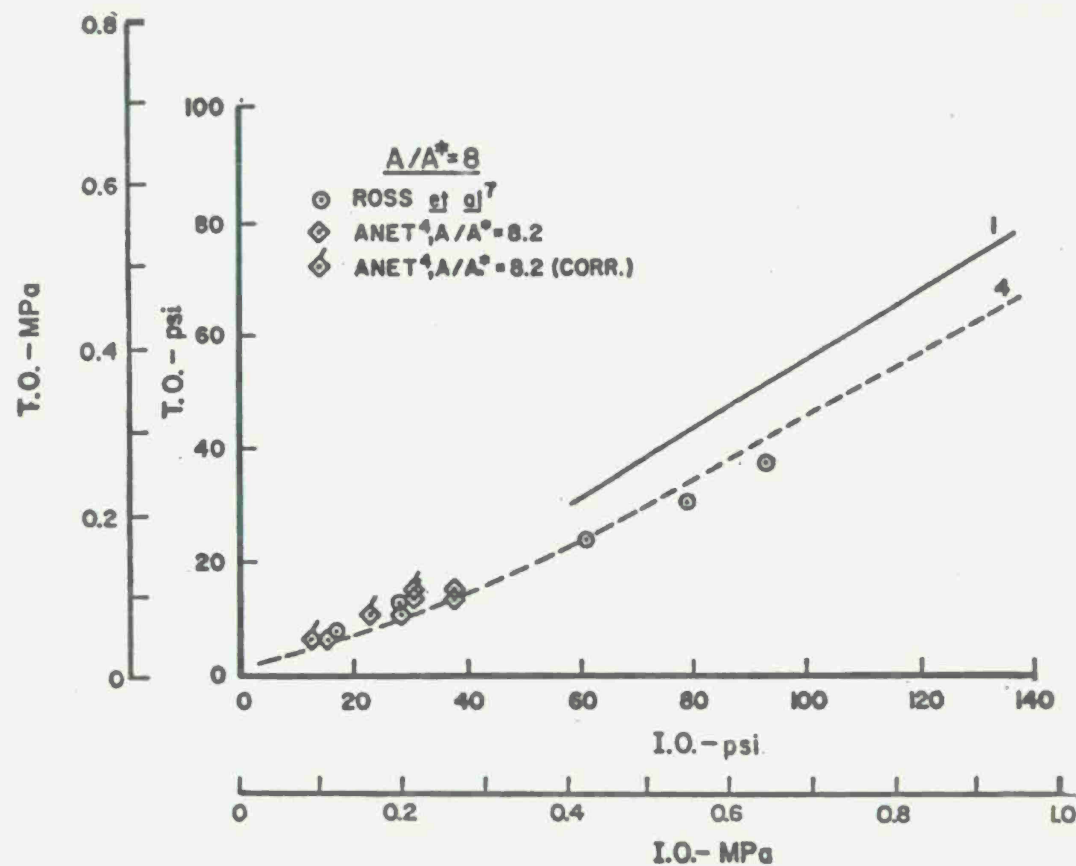


Figure 6c. Comparison of Experiment with Models 1 and 4: Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for  $A/A^* = 8$ .

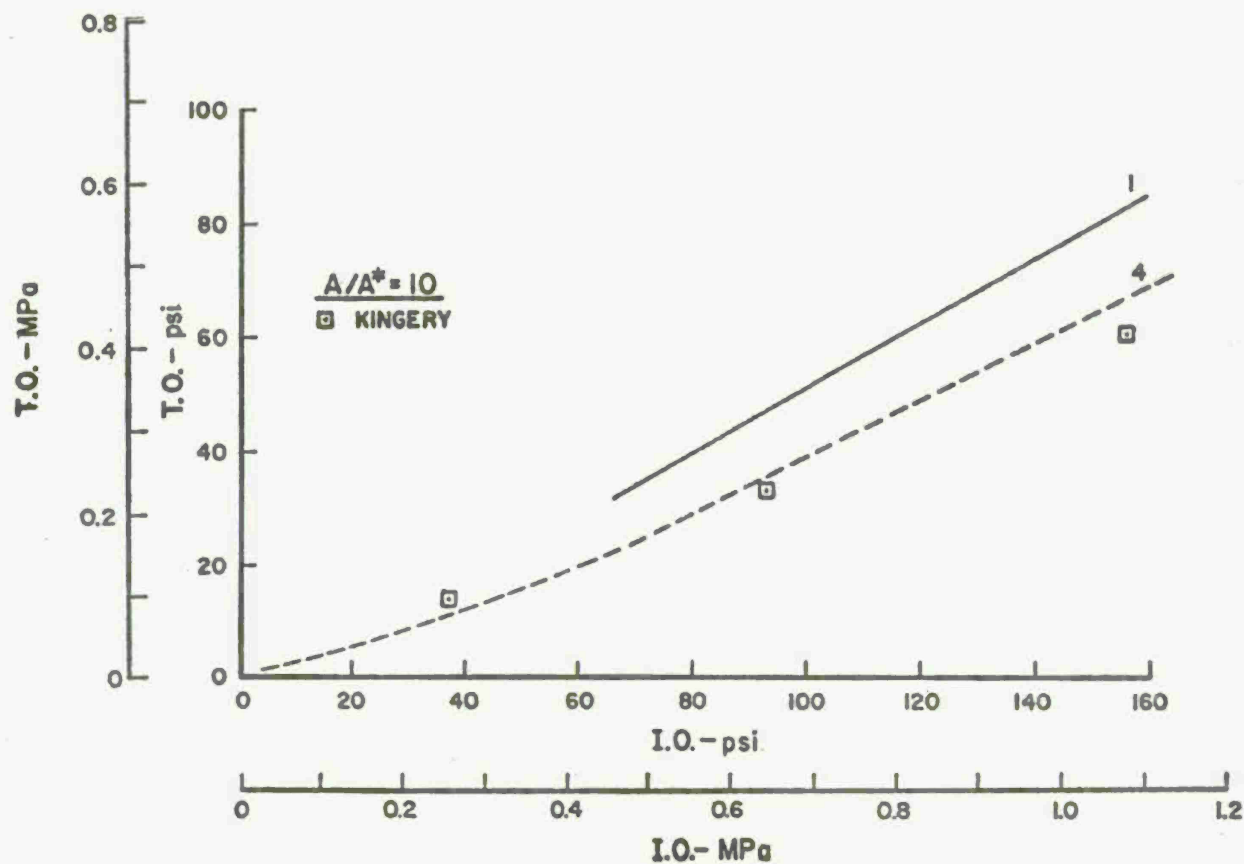
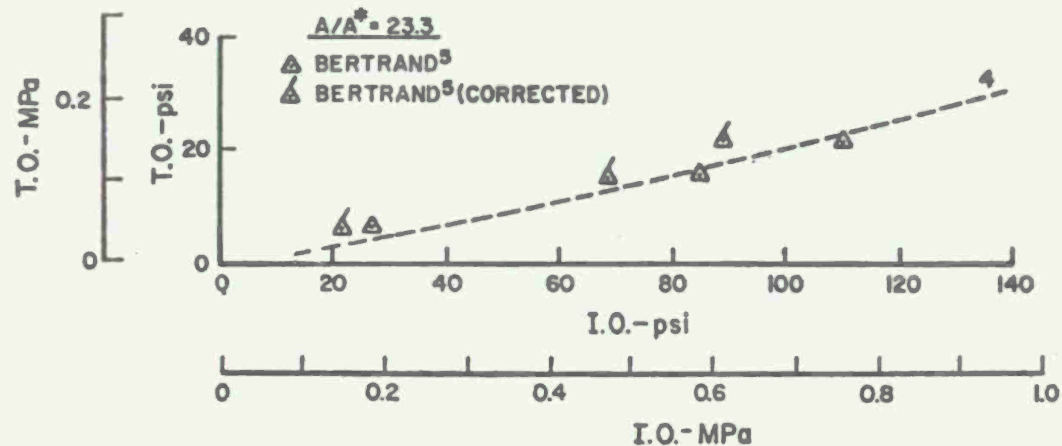


Figure 6d. Comparison of Experiment with Models 1 and 4: Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for  $A/A^* = 10$ .



35 Figure 6e. Comparison of Experiment with Model 4: Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for  $A/A^* = 23.3$ .

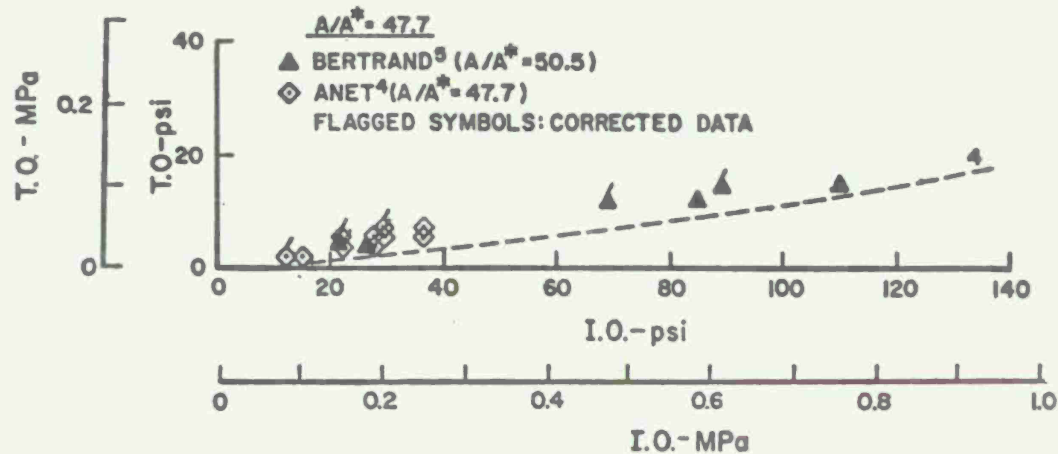


Figure 6f. Comparison of Experiment ( $A/A^* = 47.7, 50.5$ ) with Model 4 ( $A/A^* = 47.7$ ): Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.).



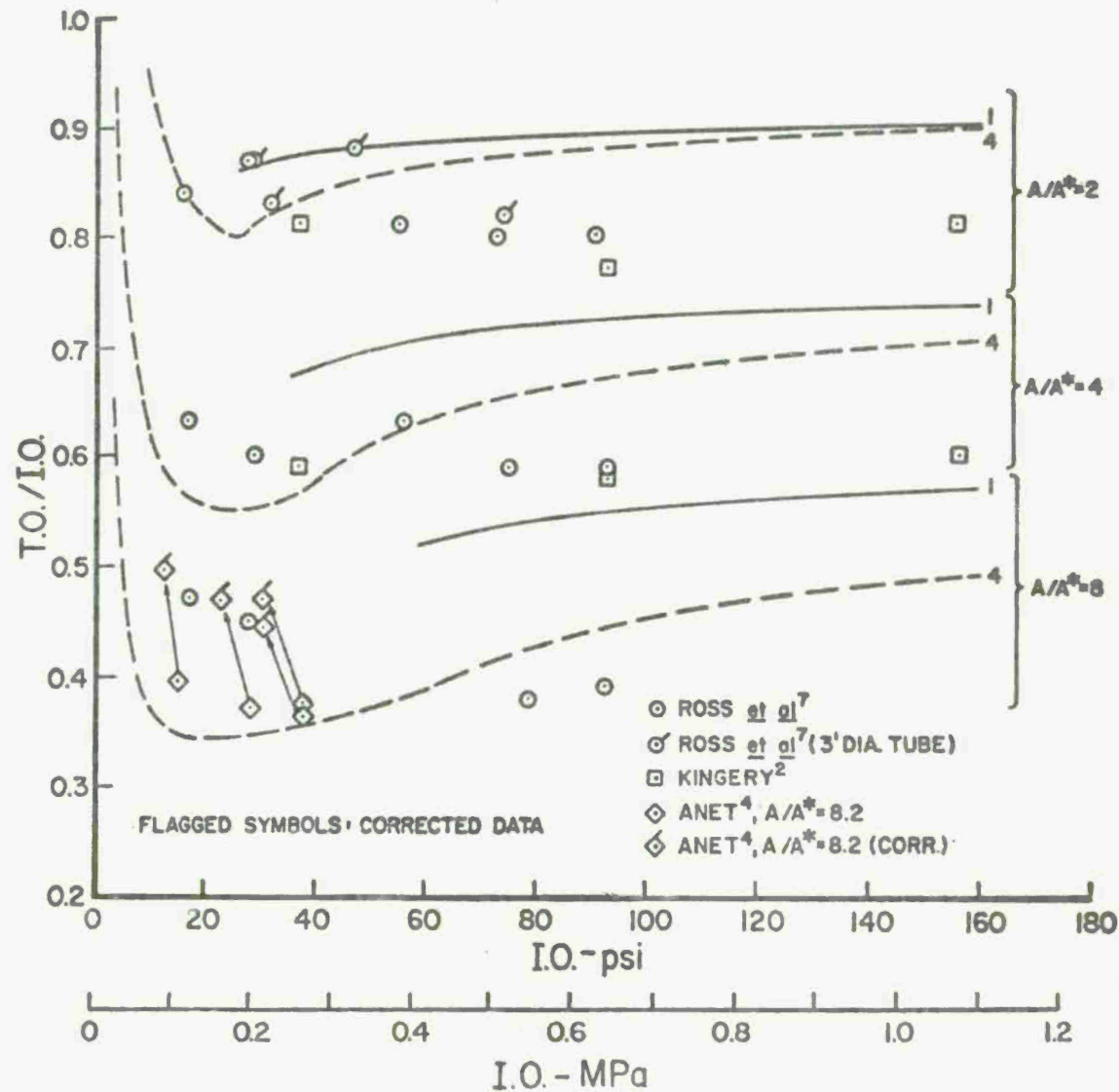


Figure 7a. Comparison of Experiment with Models 1 and 4: Ratio of Transmitted-to-Incident Overpressure ( $T.O./I.O.$ ) Versus Incident Overpressure;  $A/A^* = 2, 4, \text{ and } 8$ . Arrows indicate the shift when data assumed to be uncorrected are corrected as per discussion on page 15.

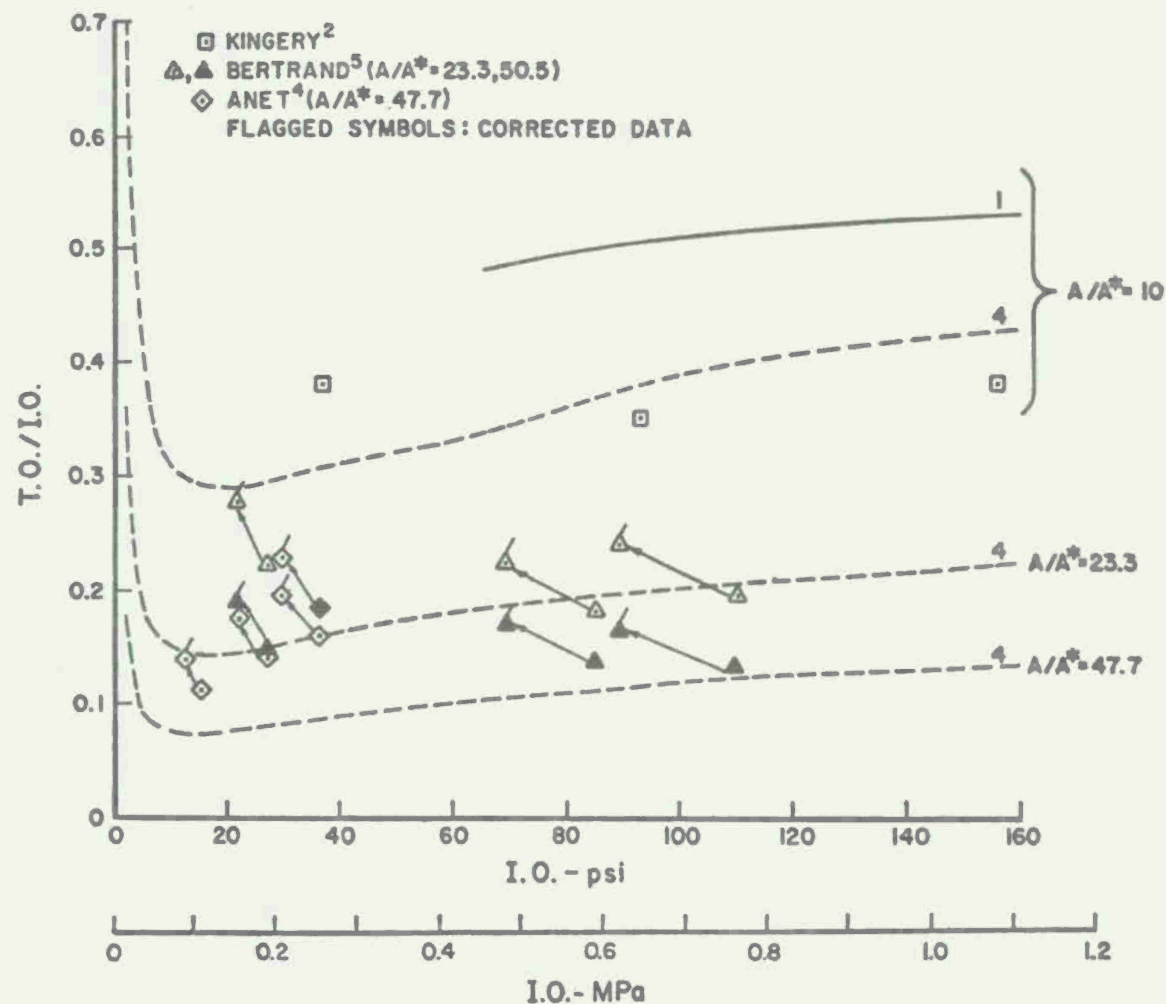


Figure 7b. Comparison of Experiment with Models 1 and 4: Transmitted Overpressure (T.O.) Versus Incident Overpressure (I.O.) for  $A/A^* = 10, 23.3$ , and  $47.7$  (and  $50.5$ ). Arrows indicate the shift when data assumed to be uncorrected are corrected as per discussion on page 15.

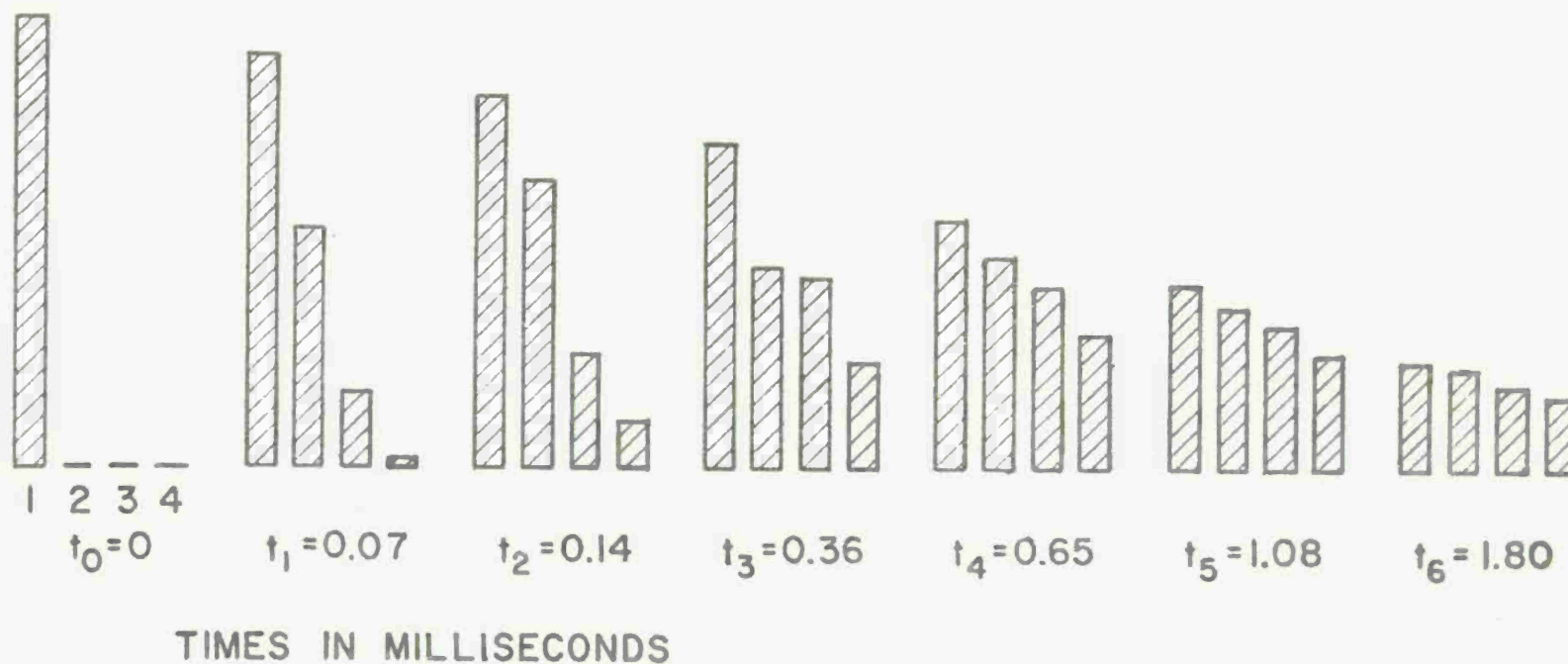


Figure 8. Pressure Measured at Several Instants in Time Between the Plates of a 4-Plate Series Array. The numbers 1, 2, 3, and 4 at  $t_0$  are the plate numbers. The incident over-pressure, pressure at  $t_0$ , is 234 psi (1.61 MPa).

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## APPENDIX: GOVERNING EQUATIONS FOR MODEL 4

### Approach

The shock wave approaching the vented structure is governed by the jump relations. For a given Mach number,  $M_{S_I} \equiv U_{S_I}/a_1$  (see Fig. 2), the equations in a shock-fixed coordinate system are:

$$\frac{u_2}{a_1} = \frac{2}{\gamma+1} \left( M_{S_I} - \frac{1}{M_{S_I}} \right) \quad (1)$$

$$Y_I \equiv \frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1} M_{S_I}^2 - \frac{\gamma-1}{\gamma+1} \quad (2)$$

$$\frac{a_2}{a_1} = \left\{ \frac{Y_I \left( Y_I + \frac{\gamma+1}{\gamma-1} \right)}{\frac{\gamma+1}{\gamma-1} Y_I + 1} \right\}^{1/2} \quad (3)$$

### Entry

As in reference 8, we assume that the shock wave is fully-reflected from the plate, and that flow into the hypothetical nozzle is established by an unsteady expansion to the state[6'] (see Fig. 2a). Again in a shock-fixed coordinate system, the governing equations across the reflected shock are:

$$Y_R \equiv \frac{p_6}{p_2} = \frac{\left( \frac{\gamma+1}{\gamma-1} + 2 \right) Y_I - 1}{Y_I + \frac{\gamma+1}{\gamma-1}} ; \quad \frac{p_6}{p_1} = Y_R \cdot Y_I \quad (4)$$

$$\frac{a_6}{a_2} = \left\{ \frac{Y_R \left( Y_R + \frac{\gamma+1}{\gamma-1} \right)}{\frac{\gamma+1}{\gamma-1} Y_R + 1} \right\}^{1/2} ; \quad \frac{a_6}{a_1} = \frac{a_6}{a_2} \cdot \frac{a_2}{a_1} \quad (5)$$

For the unsteady, isentropic expansion, we have from the Riemann condition,

$$u + \frac{2}{\gamma-1} a = \text{const}, \text{ and the isentropic relation, } p = \text{const} \cdot \rho^\gamma = \text{const} \cdot a^{2\gamma/\gamma-1};$$

$$\frac{a_{6'}}{a_1} = \frac{a_6/a_1}{1 + \frac{\gamma-1}{2} M_{6'}^2}; \quad u_6 = 0 \quad (6)$$

$$\frac{u_{6'}}{a_1} = M_{6'} \cdot \frac{a_{6'}}{a_1} \quad (7)$$

$$\frac{p_{6'}}{p_1} = \frac{p_{6'}}{p_6} \cdot \frac{p_6}{p_1} = \left\{ \frac{a_{6'}/a_1}{a_6/a_1} \right\}^{\frac{2\gamma}{\gamma-1}} \cdot \frac{p_6}{p_1} \quad (8)$$

where we compute  $M_{6'} < 1$  from the equation for steady nozzle flow:

$$\frac{(M_{6'}^2 + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}}{M_{6'}} = \frac{(M_7^2 + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}}{M_7} = \frac{A}{A^*} \frac{(M^{*2} + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}}{M^*} \quad (9)$$

Here  $A/A^*$  is the full area ratio, and, since flow through the nozzle is assumed to be a maximum for the approach condition,  $M^* = u^*/a^* = 1$ . The supersonic value,  $M_7 > 1$ , is also computed for later use.

Up to this point, the calculation has been straightforward -- no iterations -- for a given incident Mach number (or incident overpressure  $(p_2/p_1 - 1) \cdot p_1$ ) and a given area ratio,  $A/A^*$ .

### Expansion

We replace the actual unsteady expansion process by a steady, quasi-one-dimensional expansion in a hypothetical divergent nozzle. Two cases must be considered for a given  $A/A^*$ : 1) recompression of the expanded gases is required within the divergent nozzle, and 2) recompression is required after expansion to the full tube area has taken place.

When expansion to the full tube area takes place, we have the situation depicted in Figure 2d,  $M_7$  equals the value computed from Equation (9), and we proceed with the following equations for steady isentropic expansion:

$$\frac{a_7}{a_1} = \frac{a_{6'}}{a_1} \left\{ \frac{M_{6'}^2 + \frac{2}{\gamma-1}}{M_7^2 + \frac{2}{\gamma-1}} \right\}^{1/2} \quad (10)$$

$$\frac{u_7}{a_1} = M_7 \cdot \frac{a_7}{a_1} \quad (11)$$

$$\frac{p_7}{p_1} = \frac{p_7}{p_6} \cdot \frac{p_6}{p_1} = \left\{ \frac{a_7/a_1}{a_{6'}/a_1} \right\}^{\frac{2\gamma}{\gamma-1}} \cdot \frac{p_6}{p_1} \quad (12)$$

Across the recompression or inward-facing shock, which moves to the right behind the transmitted shock wave with a Mach number  $M_c$ , we compute:

$$\frac{p_8}{p_7} = \frac{2\gamma}{\gamma+1} M_c^2 - \frac{\gamma-1}{\gamma+1}; \quad \frac{p_8}{p_1} = \frac{p_8}{p_7} \cdot \frac{p_7}{p_1} \quad (13)$$

and

$$\frac{u_8}{a_7} = M_7 - \frac{2}{\gamma+1} \left( M_c - \frac{1}{M_c} \right); \quad \frac{u_8}{a_1} = \frac{u_8}{a_7} \cdot \frac{a_7}{a_1} \quad (14)$$

Across the transmitted shock wave:

$$\frac{p_9}{p_1} = \frac{2}{\gamma+1} M_{S_T}^2 - \frac{\gamma-1}{\gamma+1} \quad (15)$$

and

$$\frac{u_9}{a_1} = \frac{2}{\gamma+1} \left( M_{S_T} - \frac{1}{M_{S_T}} \right) \quad (16)$$

The solution is obtained by Newton iteration procedure to find an  $M_c$  for which the equations  $p_8/p_1 = p_9/p_1$  and  $u_8/a_1 = u_9/a_1$  are matched across the contact front. Or, the equations can be solved graphically.



Solutions are valid for a given  $A/A^*$  so long as  $M_c < M_7$ . Solutions can also be found for  $M_c > M_7$ , but this requires that  $u_7$  be negative. This unrealistic result occurs for low incident overpressures.

The limiting value of incident overpressure which satisfies the set of equations above is found for a given  $A/A^*$  when  $M_c = M_7$ , where  $M_7$  is the value computed from Equation (9). That is, the limit is found when the inward-facing shock stands at the nozzle exit. For incident overpressures less than this limiting value (for a given  $A/A^*$ ) the inward-facing shock stands in the divergent nozzle as shown in Figure A1.

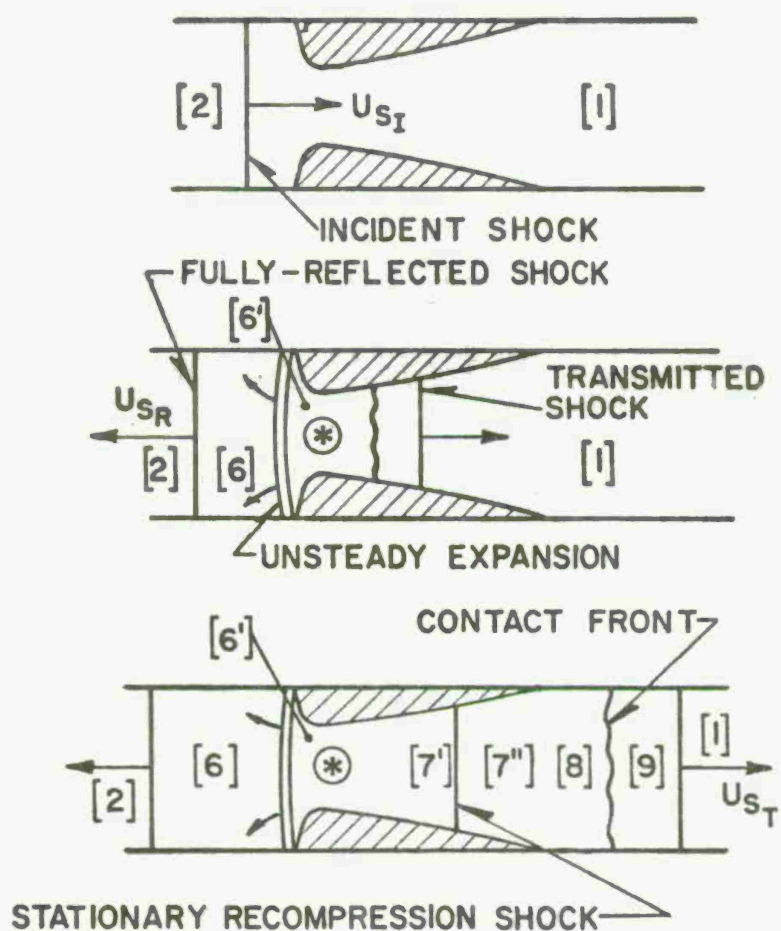


Figure A1. Sketch of Flow Model: Model 4 with Recompression Shock Standing in the Divergent Nozzle.

For this case, we seek a solution for which  $M_{7'} \leq M_7$  and  $A_{7'}/A^* = A_{7''}/A^* \leq A/A^*$  using the following equations:

For steady, isentropic expansion to  $A_{7'}/A^*$  in the divergent nozzle:

$$\frac{A_{7'}}{A^*} = \frac{(M_{7'}^2 + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}}{M_{7'}} \cdot \frac{M^*}{(M^{*2} + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}} \leq \frac{A}{A^*} \quad (9)'$$

and

$$\frac{a_{7'}}{a_1} = \frac{a_{6'}}{a_1} \left\{ \frac{M_{6'}^2 + \frac{2}{\gamma-1}}{M_{7'}^2 + \frac{2}{\gamma-1}} \right\}^{1/2} \quad (10)'$$

$$\frac{u_{7'}}{a_1} = M_{7'} \cdot \frac{a_{7'}}{a_1} \quad (11)'$$

$$\frac{p_{7'}}{p_1} = \frac{p_{7'}}{p_6} \cdot \frac{p_6}{p_1} = \left\{ \frac{a_{7'}/a_1}{a_{6'}/a_1} \right\}^{\frac{2\gamma}{\gamma-1}} \cdot \frac{p_6}{p_1} \quad (12)'$$

Across the stationary shock,  $M_c = M_{7'}$  and:

$$\gamma_c \equiv \frac{p_{7''}}{p_{7'}} = \frac{2\gamma}{\gamma+1} M_c^2 - \frac{\gamma-1}{\gamma+1} ; \quad \frac{p_{7''}}{p_1} = \gamma_c \cdot \frac{p_{7'}}{p_1} \quad (13)'$$

$$\frac{a_{7''}}{a_{7'}} = \left\{ \frac{\gamma_c (\gamma_c + \frac{\gamma+1}{\gamma-1})}{\frac{\gamma+1}{\gamma-1} \gamma_c + 1} \right\}^{1/2} ; \quad \frac{a_{7''}}{a_1} = \frac{a_{7''}}{a_{7'}} \cdot \frac{a_{7'}}{a_1} \quad (14)'$$

$$\frac{u_{7''}}{a_1} = M_{7'} - \frac{2}{\gamma+1} (M_c - \frac{1}{M_c}) ; \quad \frac{u_{7''}}{a_1} = \frac{u_{7''}}{a_{7'}} \cdot \frac{a_{7'}}{a_1} \quad (15)'$$

$$M_{7''} = \frac{u_{7''}/a_{7'}}{a_{7''}/a_{7'}} \quad (16)'$$

For steady, isentropic nozzle expansion to state [8]:

$$\frac{(M_8^2 + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}}{M_8} = \frac{A}{A^*} \cdot \frac{A^*}{A_{7'}} \cdot \frac{(M_{7''}^2 + \frac{2}{\gamma-1})^{\frac{\gamma+1}{2(\gamma-1)}}}{M_{7''}} \quad (17)'$$

and

$$\frac{a_8}{a_1} = \frac{a_{7''}}{a_1} \left\{ \frac{M_{7''}^2 + \frac{2}{\gamma-1}}{M_8^2 + \frac{2}{\gamma-1}} \right\}^{1/2} \quad (18)'$$

$$\frac{u_8}{a_1} = M_8 \cdot \frac{a_8}{a_1} \quad (19)'$$

$$\frac{p_8}{p_1} = \frac{p_8}{p_{7''}} \cdot \frac{p_{7''}}{p_1} = \left\{ \frac{a_8/a_1}{a_{7''}/a_1} \right\}^{\frac{2\gamma}{\gamma-1}} \cdot \frac{p_{7''}}{p_1} \quad (20)'$$

Equations (15) and (16) are again used to compute the conditions behind the transmitted shock wave. Again, we seek a value of  $M_c$  ( $= M_{7'}$ ) for which the equations  $p_8/p_1 = p_9/p_1$  and  $u_8/a_1 = u_9/a_1$  are matched across the contact front. Newton iteration did not work well for this latter set of equations, so the "half-interval method" was used.

# LIST OF SYMBOLS

A	cross-sectional area of the tube
a	local gas sound velocity
A*	sum of the cross-sectional areas of the holes in the plate
M	local Mach number of gas
M* = u*/a*	
= 1	Mach number of gas at sonic conditions
M <sub>s</sub> ≡ U <sub>s</sub> /a	Mach number of shock wave
p	pressure
U <sub>s</sub>	velocity of shock wave
u	local gas velocity
Y	pressure ratio across shock wave
γ	ratio of specific heats, adiabatic exponent
ρ	density
Subscripts	
1,2,---	regions indicated on Figure 2
c	pertains to inward-facing shock
I	pertains to incident shock wave
R	pertains to reflected shock wave
T	pertains to transmitted shock wave





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